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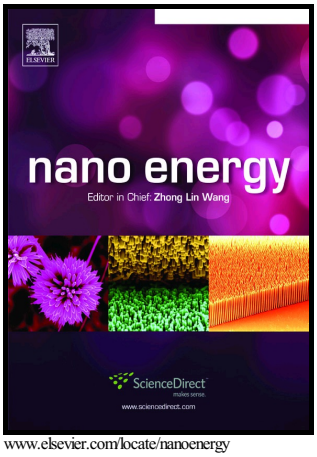

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A Structural Bionic Design: From Electric Organs to Systematic Triboelectric Generators

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Abstract

Bioelectricity and triboelectrification are well-known and widely existing phenomena in nature, and the investigation of their mechanisms and utilizations has attracted much attention for a long time. As traditional investigations suggested, the mechanism of electric organs is that the electrocytes are lined up so a current of ions can flow through them, and thus they are stacked in a sequence so that each one adds up to form a potential difference. For varieties of triboelectric generators, most of them feature extremely high voltage but limited current, which is the major challenge to pracitcal utilization. Here, we present a structural bionic design based on the microstructure of electric organs to improve the output current of

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systematic triboelectric generators. This study correlating electric organs and triboelectric generators not only benefits the practical use of systematic triboelectric generators for energy harvesting, but also offers a new approach to imitate more compositive and tunable electronic devices from biological structures.

Keywords: bionic design; triboelectric generators; energy harvesting; electric organs

1. Introduction

The bioelectricity is always interesting and inspiring, and the study of electrophysiology has progressed rapidly due to the precise and delicate experiments of many researches.[1] Among the different phenomena of bioelectricity, electric organs (EOs) of electric fishes are especially attractive because of more powerful electric discharge.[2-6] The electric eel (Electrophorus electricus) is one of a few species that uses EO to generate tunable electric field for communication, navigation, predation and defense.[7, 8] The EO composed of cells called electrocytes (muscle-derived biological batteries), which could provide a combined voltage of up to 600 V.[4] Early researchers mainly attempt to understand the mechanism of bioelectricity, identify acetylcholine receptors and discuss the evolution of EOs.[6, 9, 10] Although single electrocyte of EO can only produce a low voltage, they can add up to have a high potential difference when being stacked in a sequence. Nature is an important source of inspiration, attempts to explain function of EOs have led to the invention of chemical battery and the development of portable energy sources. [5]

Triboelectrification is an effect that is known since ancient Greek time, and the triboelectric generators (TEGs) have been invented to convert mechanical energy into electricity by a conjunction of triboelectrification and electrostatic induction.[11-14] For single TEG, there are two basic operation modes and a considerable amount of materials, which can be designed to enhance the electrical output.[15] Besides, some large-scale techniques of improving the output performance of TEGs have been developed.[16] Although

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varieties of TEGs have been fabricated, most of them feature extremely high voltage but limited current, which is the major challenge to pracitcal utilization. The power density enhancement is always the key factor of TEG development, however, to integrate multiple TEGs into a controllable power system is rare. As traditional large-scale assemblies suffer from the complex preparation processes, simple and effective strategies for integrating TEGs are imperative but currently unavailable.

With the biological evolution, electric fishes have taken full advantage of the EO to produce tunable electric field. Considering the characteristics of electric discharge and microstructure of EOs, we develop a structural bionic design of systematic TEGs with multiple-layered structure to improve the output current. By integerating an external processing circuit, the flexible systematic TEGs assembled with 5-parallel TEG has continuous current at average amplitude of 260 μA. The systematic TEGs take full advantage of the space and largely improve the output, with great potential in self-powered systems and personal electronics. Besides, the sagittal sections through the electric organs of two kinds of electric fishes of Paramormyrops were dissected to demonstrate the microstructure of multiple layers of electrocytes. Through further investigate the EOs, our human beings could make good use of the TEGs and imitate to create more complex and tunable electronic devices from biological structures.

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2. Materials and methods

In order to investigate the triboelectricity of the EOs, an assembled TEG based on the vertical contact-separation mode was fabricated. Poly (methyl methacrylate) (PMMA) is chosen to be the material as substrate because of its excellent impact strength, light weight and easy handling. A layer structure with two plates is assembled (Figure 1a), which has a thin back electrode of aluminum (Al) film and a film of EO (3.5 cm × 3.5 cm). The EO films of Apteronotus albifrons (A. albifrons) were dried by vacuum freeze drying and the TEGs

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were triggered by hands (Figure 1b). A.albifrons was chosen to be the representative of electric fishes, which is a weakly electric fish as a result of the electromotor and electrosensory systems.[17] In order to clarify the microstructure, we took some micrographs of EO. Figure 1c and Figure 1d show, respectively, an optical micrograph and a TEM micrograph of dried EO from A. albifrons, which mainly consists of sarcomeres (muscle cells) and connective tissues. Besides, the contractive capacity of sarcomeres was improved in the evolution process and the externally measured electric field arises from the synchronized activation of thousands of electrocytes. It could be speculated that the electrical field of EOs is related to their microstructure, which is multiple-layered structure.

Then the structural bionic design of systematic TEGs was further fabricated, as shown in Figure 1e. A systematic TEGs consists of five arch-shaped TEGs (ITO + PDMS+L-Cys + ITO), which are overlapped to make each one simultaneously contacted by force. A 150 μm thick indium tin oxide (ITO)-coated polyethylene terephthalate (PET) thin film (3.5 cm × 3.5 cm) was chosen to be electrode and one of the triboelectric surface. Besides, PDMS and L-Cys were mixed to be the other triboelectric surface, whose thickness is 100μm. Figure 1f shows the assembled systematic TEGs, which were connected in parallel. For the measurement of the electric output of TEGs, an external force was applied by a commercial linear mechanical motor. The open-circuit voltage was measured by using a Keithley Model 6514 system electrometer, while the short circuit current was measured by using an SR570 low-noise current amplifier (Stanford Research System).

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Figure 1. Schematic and experimental structure of the TEGs. (a) Schematic illustrations of the assembled TEG. (b) Photograph of an assembled TEG for testing the EO of the A. albifrons. (c) An optical micrograph of EO of A. albifrons. (d) A TEM micrograph of dried EO of A. albifrons. (e) Schematic of the systematic TEGs. (f) Photograph of the assembled systematic TEGs in parallel.

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3. Results and discussion

Figure 2a shows the mechanism of TEG under vertical contact-separation mode, which operates through the coupling between triboelectric effect and electrostatic induction. When a reciprocating force is applied, the intimate contact between EOs and Al results in electron transfer due to contact electrification. Negative triboelectric charges are generated on the EOs surface since it has stronger tendency to obtain electrons in comparison to Al. As the contacting surfaces are separated, the potential makes the induced electrons driven back and forth in the external circuit, which produces an alternating current. The electricity generation process and detailed theory have been extensively discussed in previous reports.[18, 19] As for the strcture of EOs, the traditional investigations represent that electrocytes are lined up so a current of ions can flow through them and they are stacked to produce a potential difference.[6, 20] Figure 2b shows the schematic of in-series electrocyte arrangement in an electric eel. Although any single electrocyte in the electric eel can only produce a low voltage, the regular in-series multiple electrocyte can generate very high voltages. This unique organization could inspire us to develope high-performance systematic TEGs, which is important for fabricating complex but tunable electronic devices.

Some researchers have investigated different kinds of connections for multiple triboelectric nanogenerators.[21, 22] When two TEGs are connected in parallel, the output voltage will be increased to some degree and the output current will be approximately doubled. When two TEGs are connected in series, there is no obvious improvement for the output performance. Besides, the output of multiple TEGs in parallel will be destructive, if each TEG works in unsynchronized condition. By investigating the microstructure of EOs, a new structural bionic design for an in-parallel connection can improve the current output of TEGs with high efficiency.As shown in Figure 2c, multiple TEGs of this structural bionic design can be triggered in synchronized condition to enhance the output. And the mechanism

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of arch-shaped TEG is based on the vertical contact-separation mode. Besides, this design is also helpful to the integration of external output circuit and the reduction of device size.

Figure 2. Schematic illustrations of the mechanism of TEGs. (a) The brief mechanism of the TEG. (b) The in-series electrocyte arrangement in an electric eel. (c) The working principle of systematic TEGs.

In the design of TEGs, the different polarity and surface structure of triboelectric materials are vital important. As shown in Figure 1a, dried EOs film of A. albifrons was processed as the triboelectric material to test the output of electric signal, and the TEGs were triggered by hands. Figure 3a shows that the short circuit current of a TEG (Al + dried EOs film of A. albifrons + Al) has an alternating behavior with maximum amplitude of 25 μA, but the peak value of I_{sc} is fluctuant. Figure 3b shows that the open circuit voltage of a TEG (Al + dried EOs film of A. albifrons + Al) has a positive peak of 40 V. By measuring with a reverse connection to the electrometer, it can be proved that the signals were generated by the TEGs.

Considering the fragile EOs film and the fluctuant output of the above TEGs, polydimethylsiloxane (PDMS) and L-cysteine (L-Cys) were mixed to replace the dried EOs film of A. albifrons. And the TEGs were driven by a linear motor to keep a stable force. The output performance of the fabricated TEGs during agitation is plotted in Figure 3c and Figure 3d. Before and after L-Cys was mixed with PDMS, the measured I_{sc} of as-designed TEGs have continuous alternating current outputs at average amplitude of 50 μA and 60 μA. The output of electric signal could be improved because L-Cys has high electronegativity.

Figure 3. Measured results of electric discharge. (a,b) The short circuit current and open circuit voltage of TEG (Al + dried EOs film of A. albifrons + Al). (c) The short circuit current of a TEG (Al + PDMS + Al). (d) The short circuit current of a TEG (Al + PDMS+L-Cys + Al).

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Based on the above investigations, different design of the structural bionic TEGs were fabricated. For the alternating current of TEG, a diode bridge can be utilized to rectify it into one direction. In order to get integrated current in previous work, each of TEGs need to be connected to a rectifier bridge and then connected in parallel.[22, 23] In our design, the systematic TEGs were connected in parallel and then connected to just one rectifier bridge. Figure 4a shows the rectified I_{sc} of single TEG driven by the linear motor, which indicates that the measured I_{sc} is comparable to the I_{sc} of Figure 3d. This arch-shaped TEG is flexible and easy to be integrated into the systematic TEGs. Compared to the single TEG, the I_{sc} of systematic TEGs of 5-parallel TEG is enhaced from 60 μA to 260 μA (Figure 4b). It is demonstrated that the structural bionic TEGs and the systematic integration could improve the output current significantly.

To deduce the law of the structural bionic design, a further study was taken to investigate the output performance on the numbers of TEG. Figure 4c shows the output performance of structural bionic design from single TEG to 5-parallel TEGs. The short circuit currents are increased with elevated numbers of TEG, while the open circuit voltages hold almost constant. This is attributed to the electrically parallel-connected design. It can be inferred that higher output current could be obtained if more TEGs are integrated to work together. Besides, the output performance of systematic TEGs could be controllable by the structural bionic design. Figure 4d shows the power output capability of the systematic TEGs of 5-parallel TEG by using resistors as external load. The output voltage increases as the resistance increases from 10^5 Ω to 10^9 Ω, while the output current follows a reverse trend. And the output power is maximized when the external load with a resistance of approximately 5×10^6 Ω. In order to get high-efficient power output from the systematic TEGs, the matched resistance of external load is pretty important.

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Figure 4. Different design of the structural bionic TEGs and the measured results. (a) The rectified short circuit current of single TEG. (b) The rectified short circuit current of systematic five TEGs. (c) The output of systematic TEGs in different number. (d) The relationship between the output voltage/current and the resistance of the external load for the systematic five TEGs.

After exploring the characteristics of structural bionic TEGs above, we further try to investigate the systematic mechanism of EOs to improve the output of TEGs. As for the evolution of the complex EOs of electric fishes, some researches have been reported such as a new molecular phylogeny for 41 species of African mormyroid electric fishes.[24] In our experiments, Figure 1d shows the microstructure of EOs from Apteronotus albifrons above, which mainly consists of sarcomeres (muscle cells) and connective tissues. And sagittal sections through the EOs of two kinds of electric fishes of Paramormyrops were dissected as shown in Figure 5a and Figure 5b. For electric fishes that give low voltage and high current, their EOs consist of many electrocytes in parallel. For electric fishes that have high voltage and low current, they have numerous electrocytes in series.[25] Figure 5a and Figure 5b show the multiple layers of electrocytes with stalklets (s) emerging from the posterior surface of the flattened cell, which join to form progressively larger stalks (St). Nerve fibers (n) synapse on the enlarged stalk and they are also on the posterior side of the electrocyte so that the electrical field of EOs can be controlled well.

In order to realize the regulation of TEGs, an external processing circuit can be used as the nerve fiber synapses, which mainly consists of rectifier bridges. As displayed in Figure 5c, two TEGs were connected in parallel to a fish model and triggered by water wave in unsynchronized condition, which can only light several LEDs. (Supporting Information: Movie S1) Although single TEG has low current, multiple TEGs can be assembled in the structural bionic design to light a large number of LEDs, as shown in Figure 5d. (Supporting

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Information: Movie S2) In this way, the systematic TEGs with external processing circuit can be directly used as a power source to drive electric devices due to its high output. Of course, the transmission mechanism of electric organs must be more complex than our mode. This work may offer a new approach to investigating the efficient integration of thousands of TEGs. Nevertheless, much remains to be done to understand how the little batteries evolved into the powerful and controllable system.

Figure 5. Demonstration of the electric organs and lighted LEDs powered by the biological TEGs. Sagittal section through the electric organs of two kinds of electric fishes of Paramormyrops showing multiple layers of electrocytes with stalklets (s) emerging from the posterior surface of the flattened cell. Stalklets join to form progressively larger stalks (St). Nerve fibers (n) synapse on the enlarged stalk, which is also on the posterior side of the electrocyte. (a) Electrocytes of Paramormyrops species. (b) Electrocytes of Paramormyrops longicaudatus. (c) Two TEGs were driven by water wave in unsynchronized condition to light the LEDs. (d) Systematic TEGs were assembled in structural bionic design to light the LEDs.

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4. Conclusions

In summary, we have demonstrated a structural bionic design of systematic TEGs with multiple-layered structure and integrated the output by an external processing circuit. On the basis of the unique structure of EOs, the flexible systematic TEGs assembled with 5-parallel TEG (ITO + PDMS+L-Cys + ITO) has continuous current at average amplitude of 260 μA. It not only largely improves the output current by external integration, but also reduces the size of total device. Besides, the similar layer structure and integration of electrical output between TEGs and EOs were also elucidated by sagittal sections through the EOs of two kinds of electric fishes of Paramormyrops. Due to the largely improved output of TEGs, the bionic

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design of systematic TEGs could lead to a new series of useful energy harvesting system for practical applications.

Acknowledgements

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Captions for the Videos:

Caption for Movie S1: Two TEGs are triggered by water wave in unsynchronized condition to light several LEDs.

Caption for Movie S2: Multiple TEGs are assembled in the structural bionic design to light many LEDs.

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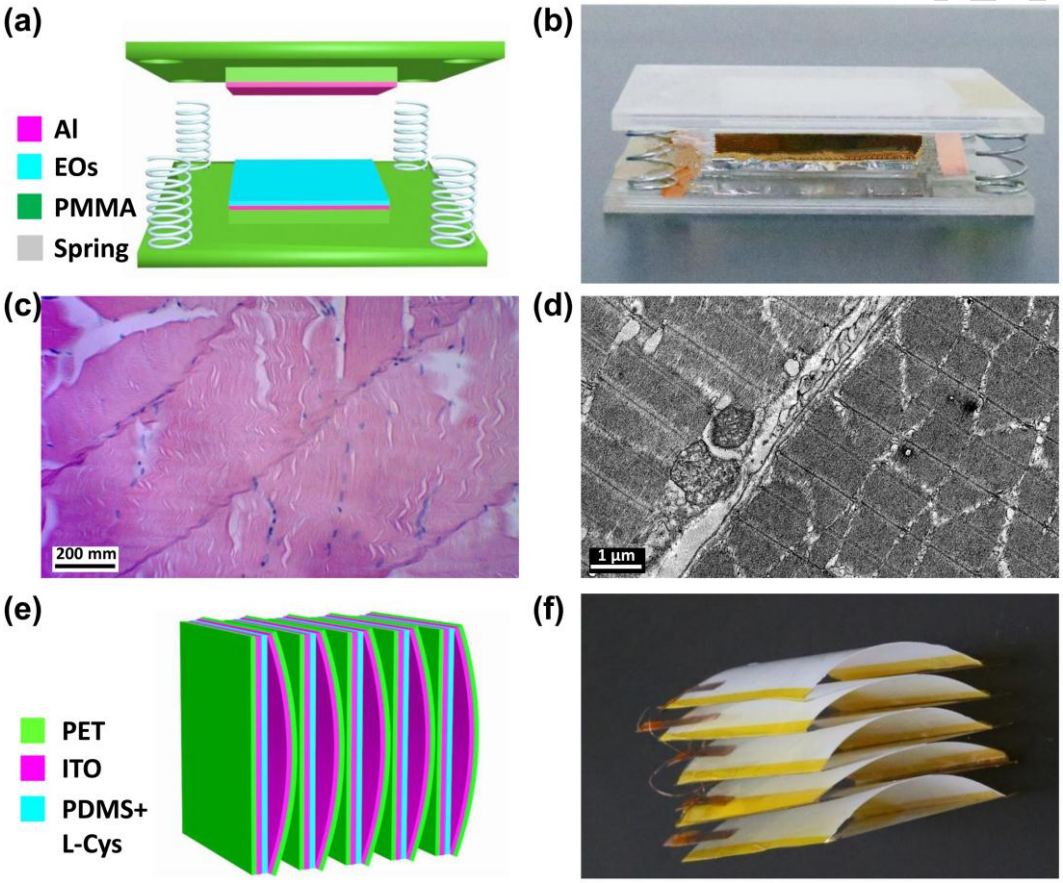
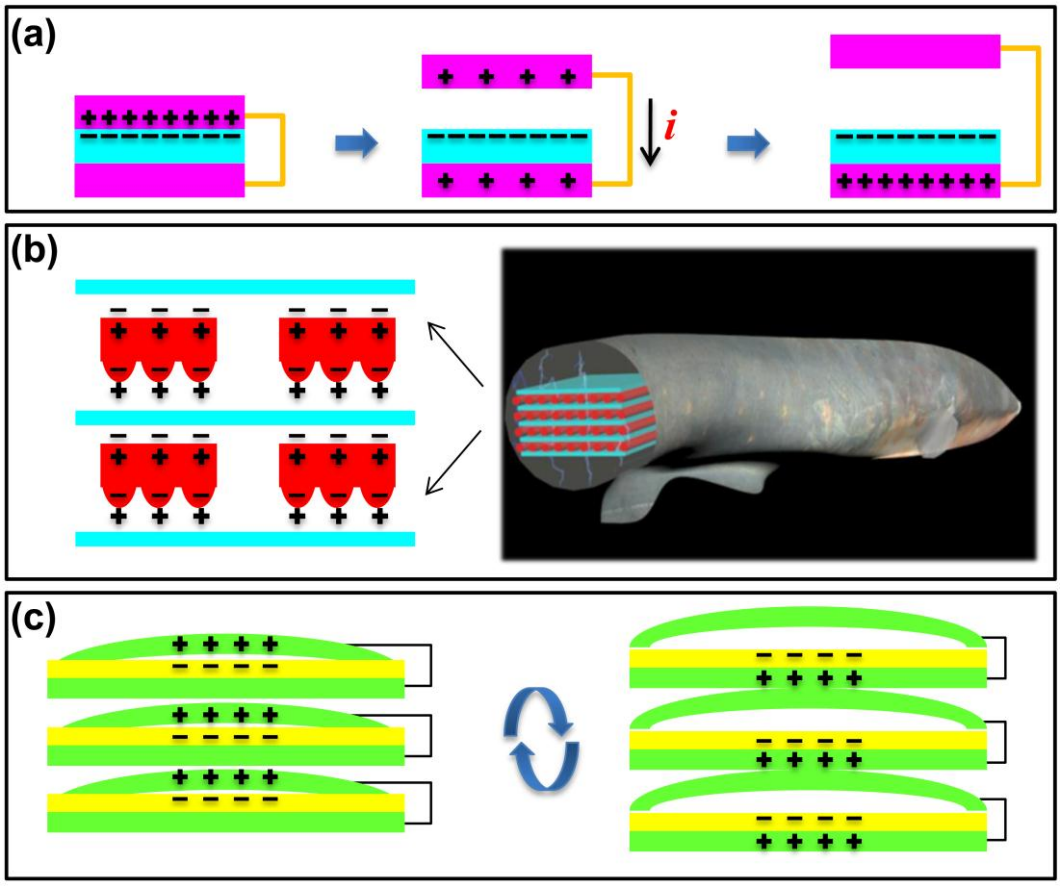
Highlights

- A bionic arch-shaped triboelectric generator is fabricated.
- An approach to systematic integration for triboelectric generator is introduced.
- The structural bionic design of systematic triboelectric generator is presented.
- A practical use of systematic triboelectric generators is shown.
- This work could lead to a series of efficient energy harvesting system.





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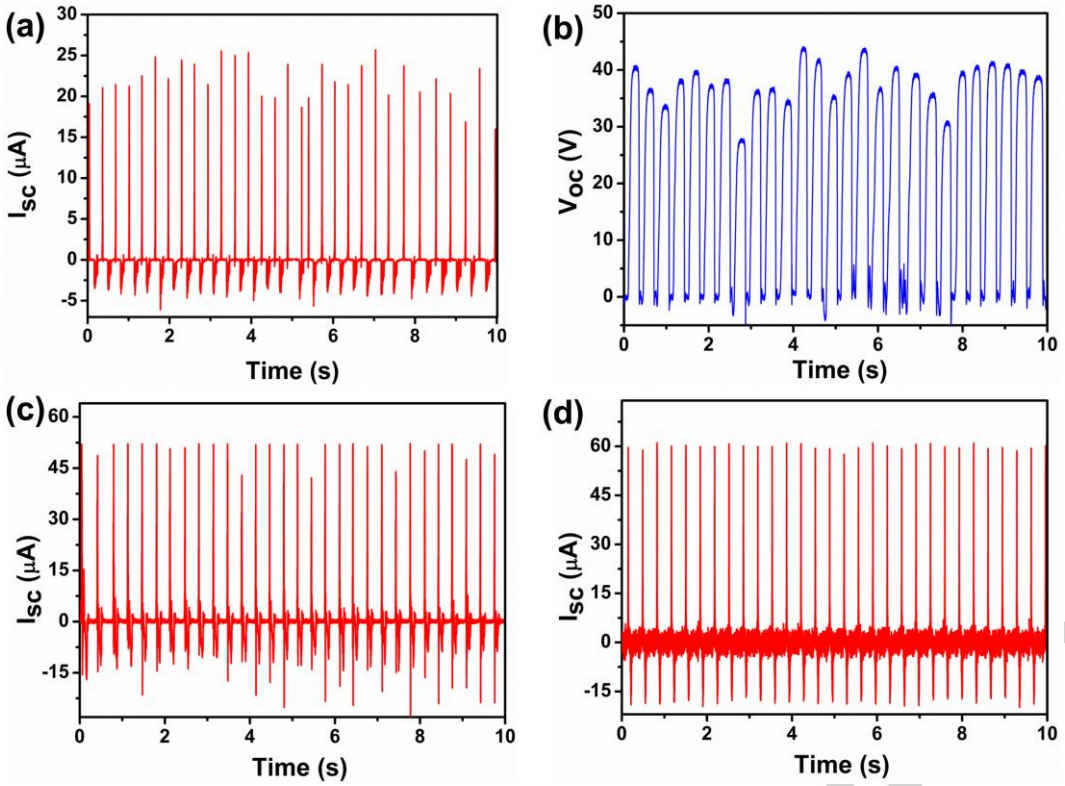
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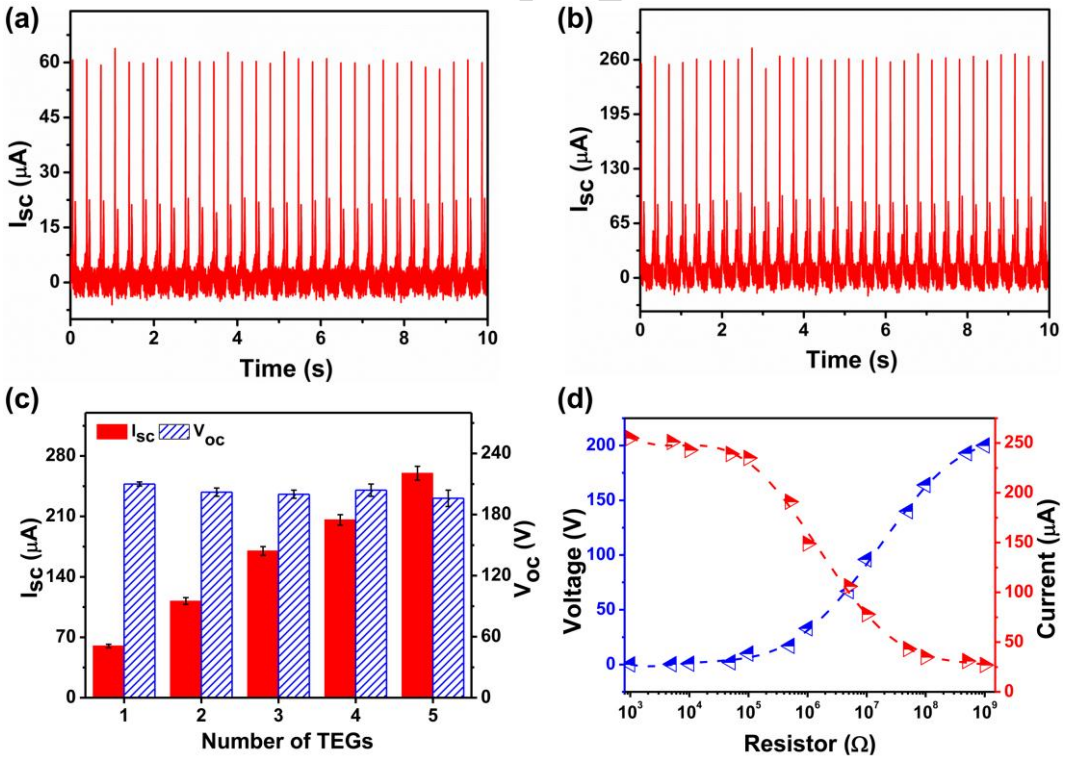
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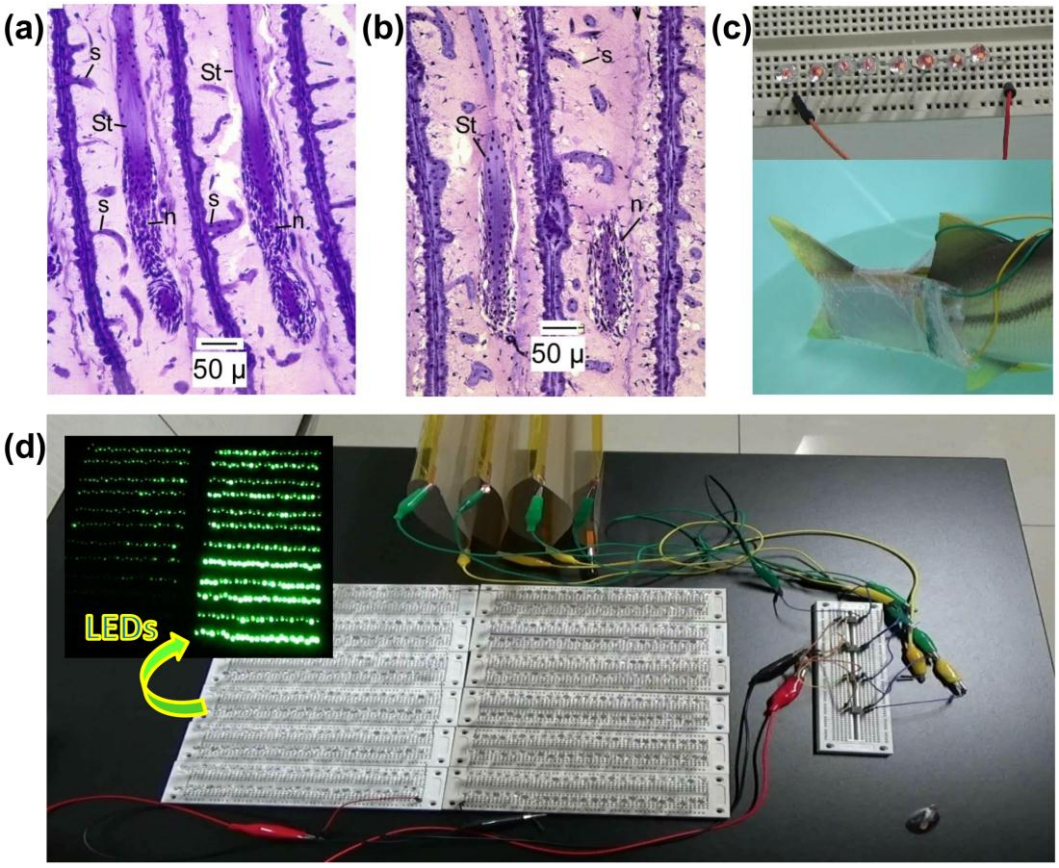

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